PRECISION MEASUREMENT OF THE HIGGS BOSON MASS AND SEARCH FOR DILEPTON MASS RESONANCES IN H $\rightarrow 4\ell$ DECAYS USING THE CMS DETECTOR AT THE LHC

By

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I dedicate this to Jacob Myhre.

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CHAPTER 1
INTRODUCTION

The universe, while overwhelmingly vast, is comprised of a curiously small number of elementary particles. These particles and their strong, weak, and electromagnetic interactions with each other are accurately described by the Standard Model (SM). A major shortcoming of the SM was its inability to predict the masses of these particles.

This dissertation presents a precision measurement of the Higgs boson mass and using LHC proton-proton collision data from Run 2 data set from

The SM was not able to predict the masses of these particles until 1964 when the Brout-Englert-Higgs mechanism suggested that It wasn't until 1964 that the Brout-Englert-Higgs mechanism gave a self-consistent way to : by breaking the electroweak gauge symmetry of the vacuum would give rise to non-zero masses of the weak gauge bosons. This would yield a secondary effect too: there should exist a fundamental scalar boson which is the quantum of the so-called "Higgs field". On July 4th, 2012, this Higgs boson was discovered.

At first glance, the universe appears to be an overwhelmingly vast and complicated place. However upon closer inspection, it is comprised of only a few different kinds of fundamental particles. Particle physics has given rise to the Standard Model (SM) which mathematically describes these constituents and their interactions with each other.

The Standard Model (SM) is an impressively accurate mathematical theory which describes the fundamental particles of the universe and the rules for their possible interactions. Problematically though, the SM predicts that all particles are massless.

Get to the Higgs boson.

Why is it important? Knowing the mass of the Higgs boson

CHAPTER 2
HIGGS BOSON MASS MEASUREMENT IN THE $H \rightarrow ZZ^* \rightarrow 4\ell$ CHANNEL

2.1 Introduction

The Higgs boson was discovered in 2012 by the CMS and ATLAS collaborations. This was a momentous achievement in particle physics because the existence of the Higgs boson was required to complete the SM. In fact, it is sometimes referred to as the "missing puzzle piece" of the SM. The Higgs boson is one of a kind: it is the only fundamental scalar particle ever discovered so far. The unique boson could be a portal to new physics (*beyond Standard Model physics*, BSM), e.g., by decaying into BSM low-mass dilepton mass resonances (Chapter **??**). In order to be certain that the recently discovered Higgs boson is truly the same as the one predicted by the SM, it is necessary to compare its measured properties to the predicted ones.

Some properties of the Higgs boson can be predicted by the SM, like - There are many results on Higgs properties: spin, charge, decay processes, lifetime, mass. - The last of these is the focus of this dissertation and is of particular importance to the Universe: depending on mH and mtop, the stability of the Universe.

ALL previous mass measurements: - Run 1: - H->2gamma VALUE - H->ZZ->4L VALUE - Run 2: - H->2gamma VALUE - (2016) H->ZZ->4L VALUE - H->bb - H->mumu - H->WW

- Why this thesis is important: - This thesis describes the methodology and results of the best precision measurement of mH to date by using the hZZ4l decay and Full Run 2 data set from CMS. - Run 2 provides more data -> more precision on measurements of Higgs properties. - In addition to more HZZ4l events, this analysis provides new techniques, specifically the VX constraint. - Predict mH for Run 3, will start soon summer 2022 and provide an approximate 300? /fb of L int. - In 2026(?), HLLHC provides even more data. ref snowmass paper.

This chapter is structured as follows:

- General overview of the Higgs boson mass measurement ingredients (Section 2.2).
- Data sets, simulation, triggers (Section **??**).
- Event reconstruction and selection (Section **??**).
- Background estimation (Irred. and Reduc. Backgrounds).
- Signal modeling: kinematic discriminant, per-event mass uncertainties, VXBS constraint, reference to ad hoc studies in appendix.

- Systematic uncertainties.
- Results.
- Summary.

SEEMS TO BE A GOOD INTRO. Should it be the intro for the entire thesis?

2.2 Analysis Overview

The first step to performing a precision measurement of the Higgs boson mass (m_{H}) is to "observe" many Higgs bosons. However, production of a Higgs boson is essentially nonexistent in everyday conditions and is still extremely rare even in the high-energy pp collisions of the LHC. At a center-of-mass energy of 13 TeV, the total inclusive inelastic cross section of two protons colliding is 70 mb TODO: CITE. Comparing this to the production cross section of a Higgs boson (TODO sigma(pptoH) = 59 pb) shows that a Higgs boson is produced in approximately 1 out of about every billion pp collisions. TODO CITE

To complicate matters further, the Higgs boson has a *very* short mean lifetime of only 1.6×10^{-22} s [1]. Thus, the Higgs boson is not directly detected by CMS but is instead *inferred* from its stable decay products that enter the various subdetectors. The question then becomes, *"Which decay mode of the Higgs boson is most useful for the measurement of m_{H}?"*. Due to its large signal-to-background ratio of approximately 2 and its uncommon final state, the $\mathrm{H} \to \mathrm{ZZ}^* \to 4\ell$ decay channel is selected and is called the *signal* process.

As is shown in Figure TODO, a Higgs boson decays into two Z bosons only 2.6% of the time. This percentage is typically expressed as a fraction, called the *branching fraction* or *branching ratio* ($\mathcal{B}$). Those Z bosons decay into opposite-sign, same flavor leptons ($\mathrm{Z} \to \ell^+\ell^-$, where $\ell = \mathrm{e}, \mu$) only 6.7% of the time, making the branching ratio of the signal process:

$$\mathcal{B}(\mathrm{H} \to \mathrm{ZZ}^* \to 4\ell) = \mathcal{B}(\mathrm{H} \to \mathrm{ZZ}^*)\left[\mathcal{B}\left(\mathrm{Z} \to \ell^+\ell^-\right)\right]^2 = 1.8 \times 10^{-3}.$$

Thus, the signal process is produced only once in about every *trillion* pp collisions.

The strategy is then to sift through the pp collision data collected and analyzed by the CMS detector (Chapter **??**) in search of all produced $\mathrm{H} \to \mathrm{ZZ}^* \to 4\ell$ events. However, events in the data

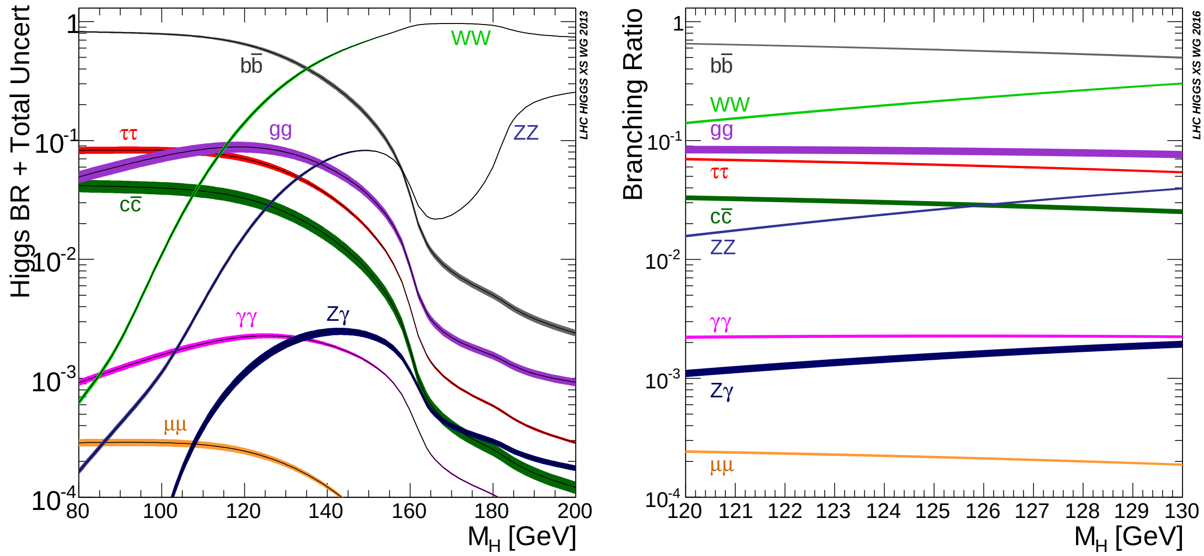

Figure 2-1. The branching ratios of various Higgs boson decays as a function of the Higgs boson mass.

sets categorized—not by the entire decay process—but by final state. Thus, this analysis requires the search through CMS data sets through the 4l final state (4e, 4mu, 2e2mu, 2mu2e) Section TODO

Once the events are selected,

This is achieved by careful event selection from the physics objects stored within the CMS data sets.

Real particles enter detectors in CMS which send signals to various electronics. Particle Flow algorithm pieces the information together to construct objects out of each event. Now, instead of just a deposit of energy in the ECAL and corresponding hits in the silicon tracker, the particle is identified as a newly produced electron. CMS records which kinds of objects came from which events and stores the information in *data sets* (TODO: ref Section future). Since there is an enormous amount of data to sift through, analysts can look at which events caused which *triggers* (TODO: ref Section previous cms triggers)

BACKGROUND - By collecting events with the 4ℓ final state, we are likely to find signal events. - It's not just the signal process which produces 4ℓ: background also makes 4ℓ (Section

FIXME).

- Before analyzing the data, however, it is important to make predictions using simulated samples (Section FIXME). - In order to sort signal from background, use simulated samples

, which is the formation of particle physics objects from data. The data collected and analyzed by CMS is not so simple so as to have $\mathrm{H} \rightarrow \mathrm{ZZ}^{*}$

This process hinges on the conservation of momentum, since in the longitudinal (z) direction the pp collision has initial and final. Specifically, the - The Z boson has a precisely measured mass of TODO a neutral particle, so the two leptons into which it decays should combine to Group two leptons together, - Form two different pairs of opposite-sign, same-flavor (OSSF) leptons - If it appears that the to select specific hzz4l events (*event selection*).

words.

REFERENCES

[1] P.A. Zyla et al. Review of Particle Physics. *PTEP*, 2020(8):083C01, 2020. doi: 10.1093/ptep/ptaa104. and 2021 update.